Low-$m_\perp$ π^+-π^- Asymmetry Enhancement from Hadronization of QGP

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We show that in sudden hadronization of QGP a non-equilibrium value of the pion phase space occupancy parameter $\gamma_q > 1$ is expected in order to accommodate the entropy excess in QGP and the process of gluon fragmentation. When γ_q is near to its maximum allowed value, pion overabundance is shown to arise at low $m_\perp$, where the charged pion asymmetry is also amplified. These effects are considered and we show that their magnitude suffices to explain pertinent experimental data obtained in 160–200A GeV Pb- and S- induced reactions.

Highly relativistic collisions of heavy nuclei are under experimental and theoretical study of which the primary aim is the discovery of the deconfined quark-gluon plasma (QGP) phase [1], and the understanding of its transformation into hadrons. We shall demonstrate how the measurement of low $m_\perp$ central rapidity abundance of charged pion yields, $dN(\pi^-)/dm_\perp$ and $dN(\pi^+)/dm_\perp$, provides a sensitive way to probe the outcome of hadronization of QGP. We will, in particular, show that the relative deformation of low-$m_\perp$ pion spectra provides a measure for chemical (particle) non-equilibrium overabundance phenomenon.

Thermal equilibration (*i.e.*, equilibration of the energy distribution) of final state hadrons is seen in particle spectra to be a well working hypothesis. This, however, does not imply chemical (*i.e.*, abundance) equilibration. Since chemical hadron abundance equilibrium is approached on the same time scale as the duration of the heavy ion collisions, it has been proposed to analyze the abundances of final state hadrons allowing chemical non-equilibrium phase space occupancies [2]. This has been applied initially only to describe the abundance of strange quarks [3], which were early on understood to be not necessarily produced rapidly enough [2]. More recently, it has been suggested that chemical equilibration of light quarks and gluons is indeed not assured at RHIC energies and beyond [4–6]. On the other hand, at SPS, the excess of pion multiplicity has been observed and understood to result from excess entropy content of the primordial high entropy phase formed in the interaction [7,8]. This leads naturally to the hypothesis of light quark overabundance generated, *e.g.*, by gluon fragmentation in hadronization of the QGP high entropy phase. This can be most easily described by counting light valence quark abundance in hadrons [9–11], as was done for strangeness.

Indeed, when the multi-particle production processes, in 158–200A GeV S– and Pb–Pb collisions carried out at CERN-SPS, have been analyzed using the methods of the statistical Fermi model [12], light quark overabundance and the associated chemical non-equilibrium was found. Overall, the results of this analysis show several features that combined do make a strong case that at least the strange hadronic particles seen at CERN-SPS, are emerging nearly directly from sudden hadronization of deconfined QGP phase of hadronic matter [11]. Moreover, the recognition that the hadron abundances are better described with oversaturation of the quark phase space allows a notable reduction of the chemical freeze-out temperature, $T_f = 145 \pm 5$ MeV, accompanied by a reduction of the baryochemical potential, $\mu_B = 200$–210 MeV, is consistent with the underlying dynamical picture. What remains open is the issue if the predominant hadronic fraction, pions, also follow the sudden hadronization model, a point we address here.

This general discussion introduced already a few statistical parameters of the Fermi model of well established meaning and we will complete the list now. Aside of the chemical freeze-out temperature T_f, further chemical parameters control hadron abundances: we note the light quark fugacity λ_u and λ_d and the phase space occupancy of light quarks $\gamma_q = \gamma_u = \gamma_d$. We recall that γ_q controls overall abundance of quark pairs, while λ_i control the difference between quarks and anti-quarks of given flavor. The difference between λ_i and γ_i is that, for quarks and anti-quarks the same factor γ_i applies, while the antiparticle fugacity is inverse of the particle fugacity. The phase space occupancy γ_q is determined to exceed unity significantly, once introduced: results obtained switching on progressively more parameters of the Fermi model show considerable improvement in the capability of the model to describe the data [13].

The proper statistical physics foundation of γ_i is obtained considering the maximum entropy principle: it has been determined that while the limit $\gamma_i \rightarrow 1$ maximizes the specific chemical entropy, this maximum is not very pronounced, indicating that a system with dynamically

evolving volume will, in general, find more effective paths to increase entropy, than offered by the establishment of the absolute chemical equilibrium [14].

It is usual to introduce the geometric average of the light quark fugacities, related to the baryochemical potential:

$$\lambda_q^2 \equiv \lambda_d \lambda_u \,, \quad \mu_q \equiv T \ln \lambda_q \,, \quad \mu_B \equiv 3\mu_q \,. \tag{1}$$

Similarly, one introduces the chemical potentials for up and down quarks:

$$\mu_d \equiv T \ln \lambda_d \,, \quad \mu_u \equiv T \ln \lambda_u \,, \quad \delta\mu \equiv \mu_d - \mu_u \,. \tag{2}$$

The difference in the number of net up $(u - \bar{u})$ and net down $(d - \bar{d})$ quarks participating in the dense matter fireball is given by the initial condition, *i.e.*, which nuclei collide. In a hadron gas, $\delta\mu/\mu_q$ varies as function of chemical freeze-out temperature as shown in [8, Fig. 1].

The relative number of particles is controlled by fugacity and phase space occupancies of the constituents. The composite hadronic particle chemical occupancy and fugacity is expressed by constituent contributions:

$$\lambda_i = \prod_{j \in i} \lambda_j \,, \qquad \gamma_i = \prod_{j \in i} \gamma_j \,. \tag{3}$$

The abundances of particles produced in QGP disintegration is most conveniently described by considering the phase space distribution of particles: the abundance of a hadron h, with j-components, freezing out from the source is

$$N_h \propto \gamma_h e^{-E_h/T} \,, \qquad \gamma_h \equiv \prod_{j \in h} \gamma_j \lambda_j \,. \tag{4}$$

For example, the effective chemical fugacities for $\pi^\mp$ composed of light quark-antiquark pair of a differing flavor is

$$\gamma_{\pi^-} = \gamma_q^2 \frac{\lambda_d}{\lambda_u} \,, \qquad \gamma_{\pi^+} = \gamma_q^2 \frac{\lambda_u}{\lambda_d} \,, \tag{5}$$

while for neutral pions we simply have:

$$\gamma_{\pi^0} = \gamma_q^2 \,. \tag{6}$$

The case of pions is, however, exceptional in another way: the SPS data analysis shows that the pion yield is governed by a large fugacity, and thus it is imperative to revert in the Fermi model to use Bose distribution function:

$$\frac{d^3 N_\pi}{d^3 p} = \frac{1}{\gamma_\pi^{-1} e^{E_\pi/T} - 1} \,, \qquad E_\pi = \sqrt{m_\pi^2 + p^2} \,. \tag{7}$$

We see that the range of values for γ_π is bounded from above by the Bose singularity:

$$\gamma_\pi < \gamma_\pi^c = e^{m_\pi/T} \,. \tag{8}$$

When $\gamma_\pi \to \gamma_\pi^c$ the lowest energy state (in the continuum limit with $p \to 0$) will acquire macroscopic occupation and a pion condensate is formed. Such a condensate 'consumes' energy without consuming entropy of the primordial high entropy QGP phase [7,8] and we cannot expect this to occur in hadronization of a high entropy phase into a low entropy confined phase. However, a sudden hadronization process will naturally have the tendency to approach the limiting value $\gamma_\pi \to \gamma_\pi^c$ in order to more efficiently connect the deconfined and the confined phases, since, as we show in Fig. 1, the entropy density is nearly twice as high at $\gamma_\pi \simeq \gamma_\pi^c$ than at $\gamma_\pi = 1$. We note that all thermodynamic quantities of interest here do not develop a singularity in the limit $\gamma_\pi \to \gamma_\pi^c$.

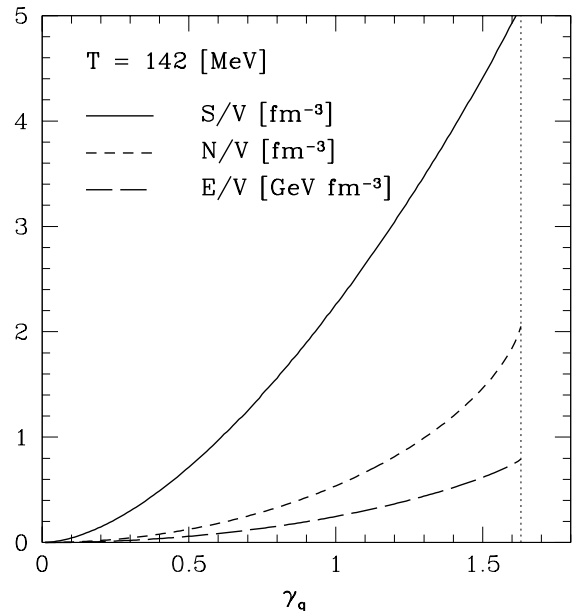FIG. 1. Dependence of pion gas properties N/V-particle, E/V-energy and S/V-entropy density, as function of γ_q (for $\lambda_d = \lambda_u$) at $T = 142 \, \mathrm{MeV}$.

We thus consider as a possible and indeed likely QGP hadronization mechanism, the conversion of the excess of entropy of the deconfined state into oversaturation of pion phase space. This mechanism can replace the more conventional approaches that also described the 'absorption' of the excess QGP entropy:

1) formation of a mixed phase which allows the volume of the fireball of hadronic matter to grow in the hadronization; the excess of QGP in entropy is converted into the greater volume of lower entropy density hadronic gas.

2) reheating which allows the entropy excess to be accommodated in the momentum 'volume' of the phase space.

Of course, both these effects can coexist, and also they can, in principle, coexist with our proposed third mechanism, the chemical non-equilibrium. In fact, which exact path is taken is only found in a microscopic description which allows for all these effects with appropriate relative rates. A model study of the dynamics of the hadronization process shows that the reaction mechanism

here proposed is possible [15], though a full understanding of the microscopic hadron phase transformation remains at present beyond our capability. However, aside of the fact that the data analysis heavily favors our proposal, we note that the conventional processes are by far more complex and thus more difficult to realize on the short time scale $\mathcal{O}(10^{-22}\,\text{s})$ available in heavy ion collisions, as compared to a rather straight forward gluon fragmentation, accompanied by recombination of quarks into pions, which is the probable microscopic origin of the large chemical nonequilibrium value of γ_q.

Let us return now to the study of pion abundances: the slight chemical asymmetry originating in the larger neutron number than proton number in heavy nuclei, leads to light quark abundance asymmetry, $N_d > N_u$, and requires that one of the charged pion fugacities (π^-) increases (towards the condensation point), while the other charged pion (π^+) fugacity is moved further away from it. The result of this is clearly visible in Eq. (7) when combined with Eqs. (5,6): as function of energy this slight change has the effect of enhancing the yield of low energy π^- over that of π^+. There is a much more significant effect when we are near to γ_π^c than it is the case for $\gamma_q = 1$ which was explored earlier [16]. In the following, we will address in detail the statistical parameters as they are determined for the 158–200A GeV interactions and presented in table I. We note that for the Pb–Pb system, the value of $\lambda_s = 1.10$ compensates the Coulomb effect distortion of the phase space of strange quarks in QGP. Thus, it is a measure of the magnitude of the Coulomb potential at hadronization, and hence of the freeze-out volume [10]. We so estimate the volume of the fireball at chemical freeze-out to be $V \simeq 2100\,\text{fm}^3$, and this value is used to check if the absolute yields of pions, and in particular here negative hadrons ($\pi^-, K^-, \bar{p}$), are consistent with measurement of the experiment NA49 [17]. We find within our approach that among the 200 'negatives' at central rapidity $\Delta y = 1$, there are (roughly) about 145 directly produced π^-, 20 $\bar{p}$ and K^-, and only about 30 π^- that arise from resonance decays.

Fig. 2 presents a case study of the effect on the thermal pion $m_\perp$ spectra. We integrate the longitudinal momenta in the range of rapidity $-0.5 < y < 0.5$ and consider the difference in charged pion yield divided by the sum,

$$D_q^\pi(m_\perp) \equiv \frac{N(\pi^-) - N(\pi^+)}{N(\pi^-) + N(\pi^+)}, \qquad (9)$$

as function of $m_\perp$, for small $m_\perp - m_\pi < 0.3\,\text{GeV}$, showing the result on logarithmic scale. The lowest line shows the small effect of isospin asymmetry in Pb–Pb collisions when the pion phase space is governed by the equilibrium chemical condition $\gamma_q = 1$; this result corresponds, for the range of our statistical parameters here applicable, to the results reported in Ref. [16]. As we move up, for each of the lines in Fig. 2, we increment $\gamma_q = 1$ by 0.1 and the thick and top line corresponds to the value implied by the analysis of the experimental results, $\gamma_q = 1.6$. The magnitude of the effect is now quite surprising (remember logarithmic scale), and most importantly, we do see a very clear sensitivity to the value of γ_q. While the 'modulator' of this sensitivity is the isospin asymmetry λ_d/λ_u, this quantity is in principle measured by the results shown in Fig. 2, since for $m_\perp - m_\pi > 0.3\,\text{GeV}$ we have:

$$D_q^\pi(m_\perp)\big|_{>0.3\,\text{GeV}} \simeq \frac{(\lambda_d/\lambda_u)^2 - 1}{(\lambda_d/\lambda_u)^2 + 1}. \qquad (10)$$

It must be stressed that the result shown in Fig. 2 must be compared to experiment with some caution, since it is just a case study aiming to show the extraordinary sensitivity of the $D_q^\pi(m_\perp)$ observable to the quantity γ_q. In order to be able to interpret actual data, one has to study the diluting pion component from resonance decay and the effect of collective flow. It can be hoped that the flow effect is small, and indeed cancelling in the pion yield ratio. The contribution of resonance decays turns out also to be rather small in the range of statistical parameters considered in view of the small chemical freeze-out temperature.
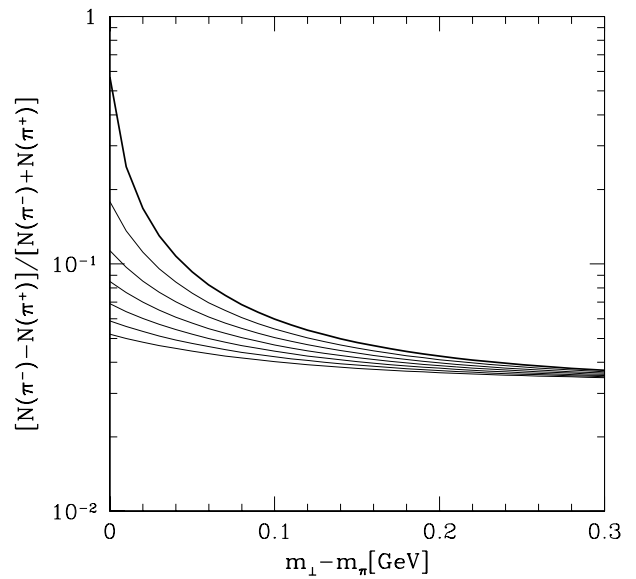

FIG. 2.   Thermal pion asymmetry $m_\perp$ spectrum, for $\gamma_q = 1$ to 1.6 (thick line) by step of 0.1, integrated in the rapidity window $-0.5 < y < 0.5$.

TABLE I.   Chemical freeze-out statistical parameters for Pb–Pb 158A GeV data [11] and S–Au/W/Pb 200A GeV data [9]. Last line is adapted from [8, Fig. 1].

	Pb	S
T_f [MeV]	142 ± 3	144 ± 2
λ_q	1.61 ± 0.02	1.51 ± 0.02
λ_s	1.10 ± 0.02	1.00 ± 0.02
γ_q	1.6 ± 0.5	1.41 ± 0.08
γ_s/γ_q	0.80 ± 0.05	0.69 ± 0.03
$\delta\mu/\mu_q$	0.07	0.04

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Given the magnitude of the γ_q-effect, we also studied in Fig. 3 the spectrum of neutral pions, which is practically indistinguishable from the average of the charged pion spectra, $(\pi^+ + \pi^-)/2$. The solid line shown in Fig. 3 are not renormalized, and (on logarithmic scale) the difference between the curves for $m_\perp - m_\pi > 0.3\,\text{GeV}$ is the result of the varying yield coefficient γ_q^2. More importantly, for $m_\perp - m_\pi < 0.2\,\text{GeV}$ with growing γ_q we see a strong up-bending of the pion spectrum. Dashed lines in Fig. 3 show results for relatively small $\Delta y = 0.02$ and demonstrate that there is just a minimal spectral deformation due to a finite central $\Delta y = 1$ integral.
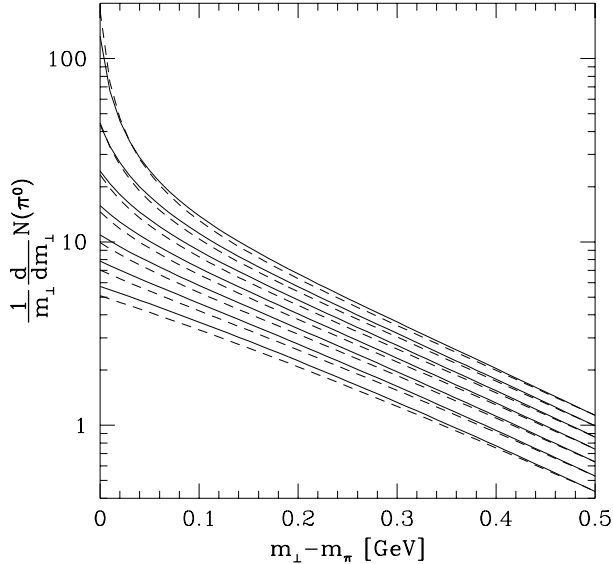

FIG. 3. Thermal π^0 spectrum, $\frac{1}{m_\perp}\frac{dN(\pi^0)}{dm_\perp}$, for $\gamma_q = 1$ to 1.6 by step of 0.1, integrated in the rapidity window: $-0.5 < y < 0.5$ (full lines), and $-0.01 < y < 0.01$ (dashed lines), the latter normalized to the result with $\Delta y = 1$ at $m_\perp - m_\pi = 0.5\,\text{GeV}$.

In order to understand the experimental pion spectra it is necessary to consider the γ_q-effect, combined with the flow effect and the hadron disintegration feeding of pion spectra. We recall here that aside of direct influence on primordial pions, γ_q also impacts the relative yield of primordial mesons compared to the yield of secondary mesons from resonance decays. Thus omission to consider γ_q-effect can mislead the data interpretation. We recall here a recent analysis of the π^0 spectra which has reached somewhat unorthodox conclusions about the freeze-out conditions as seen in Ref. [18, Table 1]. We believe that allowance for chemical non-equilibrium, specifically the introduction of $\gamma_q \simeq \gamma_q^c$ should alter the conclusions of the WA98 collaboration. Even though they study the pion spectrum at rather large $m_\perp$, γ_q impacts the cocktail mix of direct with decay pions. There is another detailed fit which also restricted the single particle pion spectra to be exactly at chemical equilibrium [19]. However, these authors do note that in order to describe the pion yield, they need a pion fugacity $\gamma_q^{100} = 1.36$,

a value which may (barely) allow their tacit assumption $\gamma_q(T = 100\,\text{MeV}) = 1$, made when they interpret particle spectra. At the higher value of chemical freeze-out temperature a range of γ_q is expected that in our opinion requires reevaluation of their results. On the other hand, the parallel analysis of Schlei and collaborators [20], which did not attempt a precise fit, and did not describe the low $m_\perp$ pion spectra, and which obtains a similar chemical freeze-out temperature as used here, appears to us to remain valid.
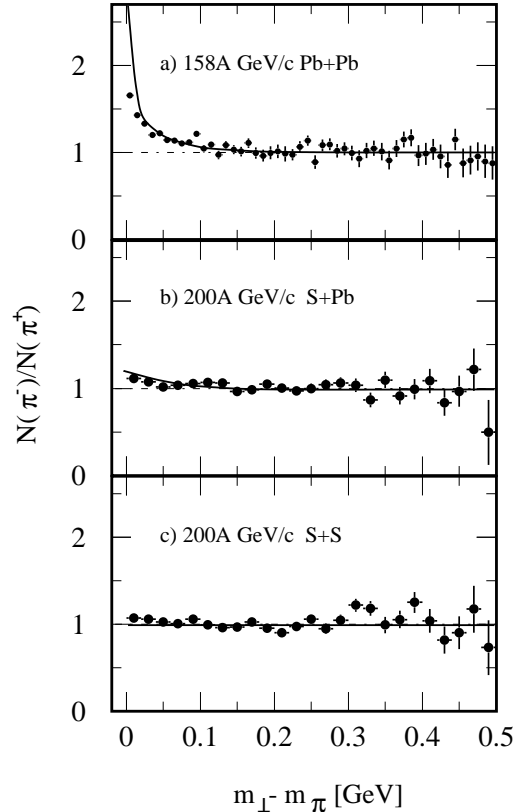

FIG. 4. Central rapidity charged pion ratio as function of $m_\perp$: data are by NA44 collaboration [21], arbitrarily normalized to unity at high $m_\perp$. The lines are our result for $\gamma_q = 1.6$, also renormalized to unity at large $m_\perp$.

It would be interesting to see what effect would arise after explicit allowance for a pion fugacity is made in these studies. Since we do not model here the effect of collective flow as was done in Refs. [18–20], we cannot ourselves answer this question in full. However, there is data from NA44 on charged pion ratios [21]. Considering: 1) the relatively small dilution of primordial pion spectra by pions from resonance decays, expected for the range of chemical freeze-out parameters shown in table I, and 2) the cancellation of the flow deformation of the spectra in spectral ratios of particles of the same mass, we have evaluated the expected γ_q-effect for the charged pion ratio results presented by NA44 collaboration [21], as shown in Fig. 4. We note that we slightly overpredict at small $m_\perp$ these results, an effect that is required given

the inclusion of hadron resonance decay feeding into the experimental data.

Several attempts have been made before to explain these NA44 data. The experimental group presented calculational results obtained with RQMD(v1.08) [21], which could not account for the data. Even though NA44 considered in their numerical model also hadron resonance decay effect, a scheme has been proposed to create the observed pion asymmetry from strangeness asymmetry [22]: in presence of finite baryon number there are more s-carrier baryons than antibaryons and more $\bar{s}$-carrier mesons than s-carrier mesons. Of course, such a description can easily be falsified by study of strange hadron abundances. In thermal models, for $\gamma_q = 1$, the NA44 asymmetry cannot be explained for the widest range of reasonable statistical parameters, a fact we have realized long ago, and which is implicit in other work [16]. These studies have thus lead to the believe that Coulomb field effects in single particle spectra are the source of pion asymmetry and a large number of authors has explored this hypothesis [23–26]. It is quite possible that in part the effect of the pion asymmetry is due to the Coulomb effect, and in part explained by the γ_q-effect here described, considering that the value $\gamma_q = 1.6$ obtained from the study of hadron abundances has a significant statistical error.

The Coulomb effect work is based on the picture of charged pions acted upon by the Coulomb field after formation at a classically well determined point. The pion asymmetry is a result of the hypothesis that the pion formation weight $W^\pm$ is actually equal for both π^+ and π^- at equal local momentum:

$$\frac{d^3 W^\pm}{d^3 p} \propto \frac{1}{e^{\sqrt{p(R_n)^2 + m_\pi^2}/T} - 1} , \qquad (11)$$

where R_n is a static or dynamic formation surface. In the WKB approximation:

$$p^\mp(x) = \sqrt{(E_\pi \mp V(x))^2 - m_\pi^2} . \qquad (12)$$

We believe that considerable improvement in these studies of the Coulomb effect is possible. In our view, the Coulomb field influences the quantum density of states obtainable from the scattering phase η. This introduces in addition to the statistical density matrix weight $\mathrm{Tr}\, e^{-\beta H}$ an additional density of states weights $d\eta^{\pi^-}/dE$, $d\eta^{\pi^+}/dE$, which due to the presence of attractive (for π^-) and repulsive (for π^+) Coulomb potential is Coulomb deformed at asymptotic pion momenta values that sample the physical size of the potential. We note that for $R_n = 8$–10 fm this effect is expected to occur for $E_\pi - m_\pi < \pi^2/2R_n^2 m_\pi \simeq 10$–20 MeV in static case. In quantum formulation the presence of (Coulomb) potential alters locally the reduced wave length $\lambdabar = \hbar/p_\pi(x)$, but not the asymptotic energy E_π of a quantum state. The work most closely related to this approach [23,26] takes Coulomb wave-functions (thus better than the

WKB illustration made above) but adds ad hoc density of state hypothesis, see Ref [23, Eq. (2)], using here the density of matter in configuration space folded with the Coulomb wave. The pion asymmetry is arising as result of substitution of Eq. (12) in Eq. (11).

Our findings have interesting bearing on the forthcoming experimental RHIC results. The data from the experiment PHOBOS [27] should in our opinion also allow to observe the γ_q-effect, both in soft pion spectra, and in pion asymmetry, provided that the non-equilibrium occupancy, $\gamma_q \simeq 1.6$, which we associated with the QGP hadronization, also occurs at RHIC — as we expect [28]. The analysis of these data should follow the pattern outlined here: from the slight inequality of the abundance at moderate $m_\perp$, according to Eq. (10), the value of chemical asymmetry can be deduced and this is used to determine the value of γ_q, given the shape of the low-$m_\perp$ spectral asymmetry following from Eq. (7). We note that Coulomb analysis also predicts a similar effect at RHIC energies [26].

We have shown that the phase space overoccupancy $\gamma_q \simeq 1.6$ of pions arising in the sudden hadronization process of the deconfined quark-gluon plasma enhances the low-$m_\perp$ pion spectra, and amplifies the abundance ratio of charged pions. We have quantitatively demonstrated the great sensitivity of these effects to the value of $\gamma_q > 1$ and have shown how this γ_q-effect helps understand SPS soft pion results of NA44 and WA98 collaborations. We conclude that the reported excess of soft pions and the asymmetry of soft charged pion spectra provides evidence for sudden and explosive hadronization (glue fragmentation) of the entropy rich deconfined phase. This finding about the mechanism of hadronization corroborates the conclusions we obtained studying high $m_\perp$ strange hadron spectra.

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